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A NEW COMPUTERIZED SINGLE FREQUENCY SEAFLOOR CLASSIFICATION SYSTEM

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ABSTRACT

The sediment classification capabilities of a new computerized acoustic system developed by Honeywell ELAC of West Germany with support from NORDA has been field tested and evaluated. The sediment classifier is an echo strength measuring device which quantitatively and qualitatively measures the acoustic signal returning from various reflectors at the surface and within the sea floor. It accomplishes this by measuring the echo return amplitude and pulse character in ten adjustable width time windows which correspond to depth increments in the sediment. Through a microprocessor, the system is then able to apply algorithms based on multilayer acoustic theory to compute acoustic impedance for each of the depth increments in the sediment. This profile of sediment acoustic impedance is then used in conjunction with other algorithms, primarily based on relationships developed by Hamilton [1], to predict sediment structure and type and various geotechnical properties such as attenuation, density, porosity, sound velocity, and grain size.

INTRODUCTION

An immediate need exists in both the military and civilian communities for a seafloor classification system which will accurately classify sediment type and predict selected geotechnical properties of the sea floor while in a rapid survey mode. In particular, the remote and rapid determination of seafloor properties has civilian application for pipeline routing, structure siting, evaluation of geologic hazards, and environmental assessment. Historically, seafloor properties have been determined through the collection of sediment at discrete points using various sampling techniques and seismic surveying, which was then followed by extensive laboratory analysis. An underway rapid survey seafloor classification system could eliminate approximately 90% of the samples now collected for sediment property delineation while discriminating and identifying transitional trends of sediment properties areally because data are collected continuously along tracklines.

In recent years numerous attempts have been made using differing approaches to develop instruments and techniques to predict seafloor sediment properties [2 - 11]. Initial tests of these instruments have produced varying degrees of success. However, as the technology and our knowledge of the interaction of acoustic energy with seafloor sediments has evolved, so has the feasibility of a remote acoustic seafloor classification system.

This paper describes the system and delineates the predictive capabilities of a new state-of-the-art computerized acoustic sediment classifier developed by Honeywell-ELAC of West Germany with support from NORDA. This sediment classification system was first tested at the Naval Coastal Systems Center (NCSC) in 1982 and is called the Remote Acoustic Seafloor CLassifier (RASCL). This system, at the time of the test, consisted of a modified high resolution echo sounding recorder, a microprocessor controlled echo strength measuring device and a 15 kHz narrow beamwidth (12°) transducer. During this test, the system was configured like a conventional echo sounder with the transducer suspended in the water column while the boat transited the test areas along predetermined tracklines. Data was output to an analog paper recorder in the form of echo amplitude versus travel time with an additional display of relative echo strength as continuous lines on the record (Fig. 1). With a soft sediment, the instrument displays the lines very close together, indicating little reflectance of the acoustic signal. As the echo return from a depth interval increases, the distance between the lines also increases giving an indication of a more reflective sediment such as sand. Values of echo strength correspond to an average measurement of reflected energy over the time interval set and not discrete sediment layers. At the time of the test, no digital recording of the echo strength was possible although it's output was available at a serial (RS-232) computer interface. This left the interpretation of the echo strength lines on the analog record to the operator which required a subjective decision as to the sediment type and consistency based on his experience with the system. However, it was possible to differentiate sandy sediments from muds. During this test, a good correlation was found between the sediment porosity estimated from the echo strength lines on the analog record and the porosity measured on ground truth samples at the various test sites. This correlation indicated that the system had promise as a sediment classifier if the echo strength data could be output to a computer where data could be stored, impedance values of each of the sediment time windows could be computed, and through empirical relationships, estimates of the sediment structure, type and various geotechnical properties could be made.

In 1984, NORDA purchased a RASCL system similar to that demonstrated at Panama City, FL earlier. NORDA also contracted Honeywell ELAC to develop a software package which would allow the recording of the raw echo strengths from each of the 10 successive sediment depth intervals in computer memory, while filtering, deconvoluting and displaying structure, impedance, sediment type, or various geotechnical properties in real time as tracklines are run. NORDA took delivery of the software package in May 1985 and the first field test of the complete system was run off Gulfport, MS in June 1985.

NCSC conducted more tests of sediment classification systems during the fall of 1985 [12]. NCSC contracted NORDA to demonstrate the computerized RASCL system in December 1985. NCSC also contracted the Naval Oceanographic Office to collect 18 sediment cores

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along tracklines across six test sites off Panama City (Fig. 2) that were used for ground truth in the evaluations of the sediment classifiers. This core data has been compiled and published by the Naval Oceanographic Office [13].

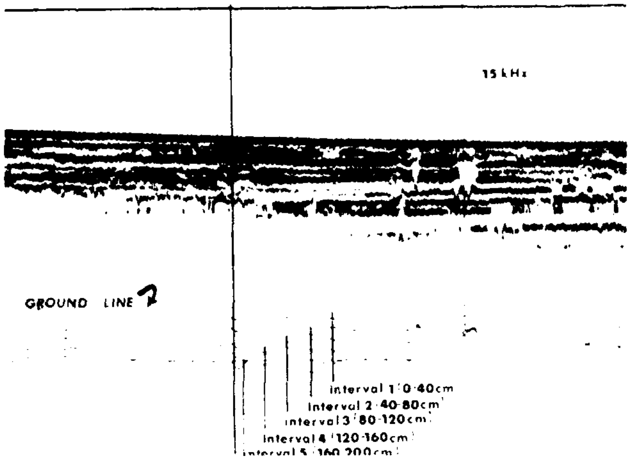

Figure 1. Example of an RASCL analog record showing the display of the echo strength lines.

This paper documents a portion of the results of the evaluation tests conducted at Panama City for NCSC by NORDA. During these tests the system collected data with a 15 kHz and a 30 kHz transducer along a series of tracklines across the six well defined and ground truthed test areas. The results obtained with the computerized sediment classifier were then compared to the ground truth core data with the results from two of the sites, one consisting of a hard sand bottom (Gulf Site) and the other a soft muddy sediment (Battleship Buoy Site), presented here.

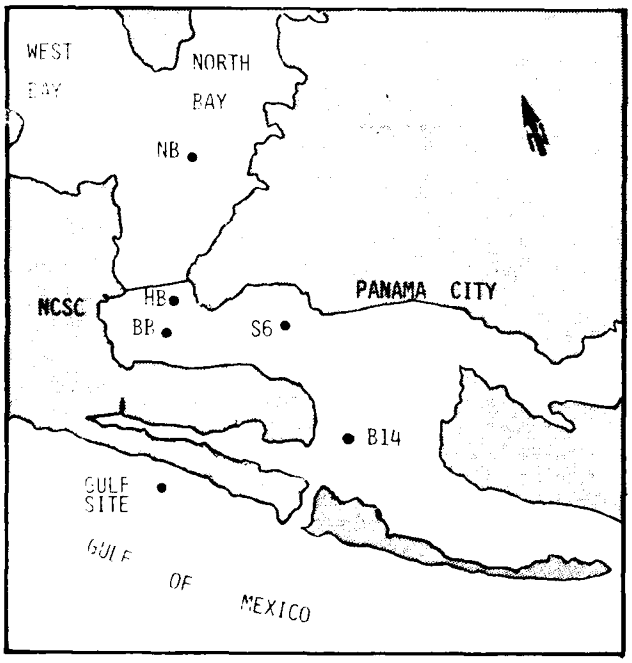

Figure 2. Panama City test site locations: Gulf Site and Battleship Buoy (BB).

SYSTEM DESCRIPTION

Hardware

The RASCL consists of four hardware components: (1) a central signal processor and system controller, the EMG2; (2) an analog recorder, the LAZ 72; (3) a transducer, either the LSE 179 or LSE 131ZR (15 and 30 kHz, respectively); (4) and a central data storage and processor which is a Digital Equipment Corporation (DEC) PRO 350 desktop computer (Fig.3).

The EMG2 is microprocessor-controlled and is the central processor of the echo strength measurements. This unit provides adjustments for the various configurations of the complete system which include digital depth measurements, signal processing, echo strength measurement, and data output display.

The EMG2 was specifically designed to investigate the structure and geological features of the sea floor. It is based on conventional echo sounding technology but is capable of quantitative measurement of the returning echo intensity. It functions as a precise digital depth measuring device which is able to recognize the sediment-water interface even in extremely soft sediments. A fixed velocity of 1500 m/sec is used to compute water depth below the transducer. Water depth is displayed on a four digit LED indicator either in decimeters or meters depending on water depth. A gain switch is provided which increases the contrast of reflectors in the sea floor through the use of a depth controlled amplifier which is programmable to the transducer being used and is capable of up to a 40 dB increase in processed signal contrast.

The EMG2 has sophisticated electronic circuitry which permits the quantitative measurement of the returning echo strength either from the sea floor or from objects in the water column. These circuits allow measurement of echo strength in ten successive depth intervals in the sea floor. The width of these intervals is switch selectable in 10, 20, 40 or 80 cm increments.

This system will suppress anomalies in echo strength due to ship motion or reflection conditions by averaging the measured echo strength of each depth interval over an adjustable number of sounding periods from 1 to 64. An echo strength amplifier also is provided which allows gain adjustment between -6 dB and +6 dB in 2 dB increments.

Output from the EMG2 is displayed on the LAZ 72 recorder similar to a conventional high resolution sub-bottom profiler where the echo amplitude versus travel time is presented graphically. The relative echo strengths of either the first or second five of the ten successive switch selectable time intervals are displayed as continuous lines across the chart (Fig. 1). The echo strength of the first depth interval is the difference between the ground line and the first line. The echo strength of the second depth interval is the difference between the first and second lines below the ground line and the third, fourth, and fifth intervals are displayed similarly. In this way no two echo strength lines can cross each other.

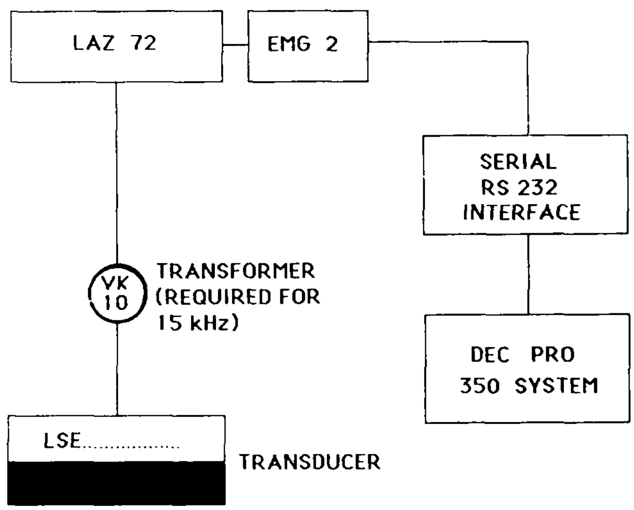

Figure 3. Hardware schematic of the computerized RASCL sediment classification system.

The echo strength also is output to the DEC PRO 350 via a serial RS232 computer interface which stores the raw echo strengths for each of the ten intervals of each ping on the computer hard disc. The computer is then able to normalize, filter, deconvolute and display on its color monitor either the unfiltered echo strengths, filtered echo strengths, impedance, or sediment structure and sediment type in real time while a trackline is being run. Controls on the recorder allow the selection of pulse width (0.3, 1.0 or 3.0 ms), power output (100 or 1000 w), depth range (15 combinations) and echo amplification (switchable in 11 steps of 6 dB each). The LAZ 72 triggers the output pulse by its styli and is operable in either a one or two styli mode. Other controls include an AV/TV switch, selection of 20 log or 40 log in the TV mode, chart speed (5 speeds and off), depth reference lines which divide the paper into 5 equal increments and a contrast booster.

Two transducers have been used with the computerized RASCL system; a 30 kHz (LSE 131ZR) and a 15 kHz (LSE 179). Transducers of several other frequencies are also available and for use simply require change of the transmitter and receiver boards The LSE 179 transducer can be operated at either 15 kHz or 30 kHz. Both transducers have narrow cone angles of only 12 degrees. The LSE 179 operated in the 30 kHz mode, has a cone angle of only 6°.

The DEC PRO 350 computer system consists of a central processing unit (CPU), keyboard, printer, and high resolution color video monitor. The CPU has 512 Kbytes of main memory, a 10 Mbyte hard disc, and dual 400 Kbyte floppy disc drives. An extended bit-map graphics module has been added to the CPU to output the sophisticated color display of impedance and sediment properties to the RGB color monitor. The computer operating system is DEC's P/OS. The software that is used for data storage, display and output uses this operating system and the PRO Tool Kit extensively.

<u>Software</u>

The software package used with the RASCL sediment classifier was developed by Honeywell ELAC under contract to NORDA. It was designed to be a very flexible research tool such that as the user's knowledge of the system increased, he could then input this knowledge into the software to produce improved results. The software is menu driven, similar to DEC's P/OS, which makes it user friendly with a minimal amount of training. Pascal was used as the software language since it is a very structured language and any necessary modifications would be straightforward.

The software package provides a relatively simple way to store data (echo strength, water depth, and time) and allows the user to do extensive data reprocessing and interpretation (Fig. 4). Once the raw echo strengths are stored on the hard disk, this data may be processed through three separate databases to output sediment structure and type, impedance, and several geotechnical properties such as wet unit weight, porosity, sound velocity, attenuation and mean grain size for each of the 10 depth increments (Fig. 5). While the data are being collected, the operator has the option of displaying unfiltered echo strengths, filtered echo strengths, or sediment structure and sediment type in a scrolling tabular format on the CRT. It is also possible to output a 16 color scrolling display of sediment impedance with depth of the 10 intervals along with time, water depth and a sediment structure code.

Three databases are very important portions of the RASCL software: Database A determines the impedance profile of the seafloor sediment; Database B predicts the sediment type; and Database D estimates the various geotechnical properties. Databases A and B work in conjunction with each other to output impedance, sediment structure and sediment type. All three databases are used in conjunction with each other to output the geotechnical property estimates (Fig 5).

METHODS

<u>Field Methods</u>

RASCL was towed in a rapid survey mode along tracklines across the six test areas (Fig.2). The tracklines chosen were along ranges previously established by NCSC and included a start point, a midpoint or center, and an end point. The midpoints, along these tracklines, constitute the primary test site. Navigation was done by a range and bearing method where the boat was driven along a particular course determined by lining-up two landmarks on shore.

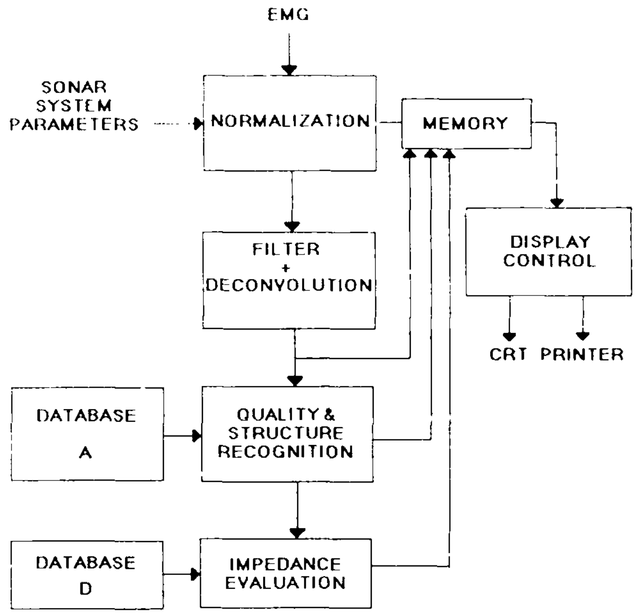

Figure 4. Schematic of software structure used during data collection.

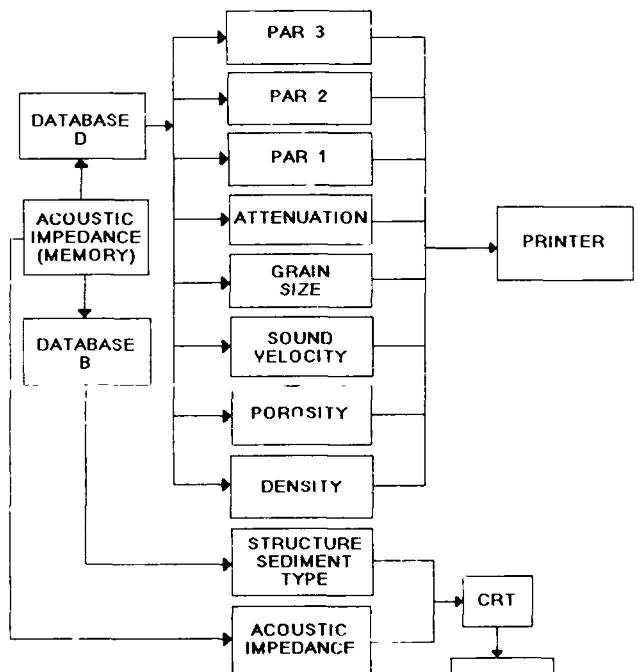

Figure 5. Schematic of software structure used during data reprocessing.

Eighteen high quality hydroplastic gravity cores and short diver cores were collected for ground truth [13]. The hydroplastic corer collects relatively undisturbed cores up to several meters in length in soft sediment. The diver corer was used at several of the sites where the hydroplastic corer could not adequately sample the harder sediments. They proved to be of limited value in this study because of their short length (maximum of 43 cm) representing only the first one or two depth increments of the ten echo strength time windows sampled by the acoustic classifier.

Sediment Analysis

After collection, the cores were sealed, labeled and transported to the Naval Oceanographic Office Sediment Laboratory. They were stored vertically in a high humidity refrigerator at 4°C from the time of collection in October 1985 until they were analyzed in April 1986. The laboratory procedures used for the core analysis are generally standard methods of the American Society for Testing and Materials [14]. A detailed description of the laboratory procedures used on the cores can be found in Ingram and others [13].

RASCL Data Collection

During the Panama City tests, the RASCL 15 kHz transducer was towed on a catamaran designed by NORDA specifically for this purpose. The catamaran provided buoyancy for the 80 kg transducer and isolated it from most of the ship's motion. The catamaran was towed from an outrigger off the stern quarter of the boat, which allowed the transducer to be towed approximately three meters away from the boat and outside its wake. The 30 kHz transducer was towed in a "tadpole" type towbody suspended from the arm of the ship's crane about 3 m off the stern quarter.

The 15 kHz data was collected using a 40 cm depth increment. Data results are more representative of the sediment increment sampled if at least four wavelengths of the signal are maintained in this increment. Since one wavelength of the 15 kHz signal is approximately 10 cm, the 40 cm interval was used for all the 15 kHz data collection.

The 30 kHz system was operated in a 20 cm increment mode for all data collected in order to double the sensitivity of the data compared to the 15 kHz system. Again, four wavelengths were maintained in the sediment interval sampled since the wavelength of the 30 kHz signal is approximately 5 cm.

All of the RASCL data collected was taken using a pulse repetition rate of 0.5 seconds and a pulse length of 0.3 m/sec. The raw echo strength data was stored on the computer hard disk as individual pings and in the 10 depth increments. Before the data was displayed on the color computer screen, a moving-center average is made in the EMG2's microprocessor over 32 pings. Therefore, the data displayed is an average of data collected 8 seconds before and 8 seconds after the present time. All of the tracklines at Panama City were run at a constant shaft RPM and averaged 1.7 m/sec (3.3 knots).

RASCL Data Analysis

All of the RASCL data was reprocessed in the laboratory using the moving-center average across 32 pulses since it was collected this way. Each pulse was used in the average. A normalization factor calculated for the 15 kHz system during calibration was used to reprocess this same data. The normalization factor for the 30 kHz system was adjusted downward because of the 20 cm sediment increment used. This normalization factor was adjusted so that the 30 kHz system produced an impedance value very close to the impedance value calculated by the 15 kHz system over the same site. Thus, both frequencies should predict the same sediment type or geotechnical property for the same area of the sea floor.

Databases were developed and used to predict sediment structure and type, density, porosity, grain size and compressional sound velocity during laboratory reprocessing of all of the data.

RESULTS

Gulf Site

The sea floor at the Gulf site (Fig. 2) is relatively flat with a slight decrease in water depth from 13.2 m at the start of the track to 11.5 m at the end (Fig. 6). The sea floor at the center consists of two known sedimentary layers. The surface sediment is composed of a fine, loosely compacted, quartz sand with a small amount of shell material and sand dollars laying on the sediment surface. The thickness of this layer varies from 20 to 30 cm. Below this surficial sand is a very dense mixture of sand and shells embedded in a matrix of compacted clay. This layer is probably indicative of a mudflat environment during a lower stand of sea level. Since the divers were only able to push a diver-held core 22 cm

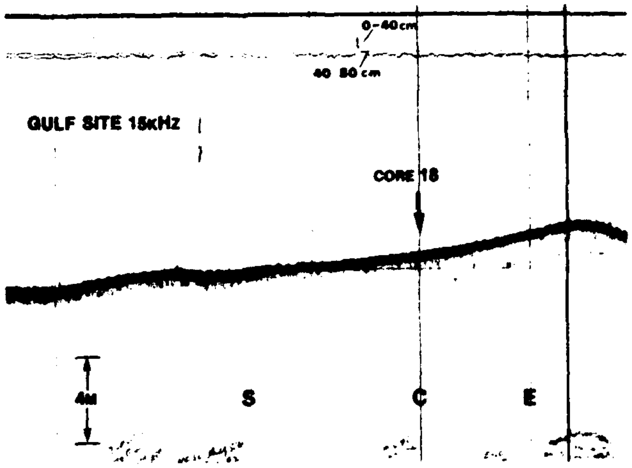

Figure 6. Gulf Site 15 kHz analog record.

into the sea floor, it is assumed that the corer encountered this hard layer at that depth. This would indicate that the thickness of the loose fine sand at this site is approximately 22 cm.

Both the 15 and 30 kHz transducers were operated over the Gulf Site. The 15 kHz record shows one hard layer of the 0 - 40 cm interval and estimates an impedance value of 3.25 for this interval (Table 1). In this instance, the RASCL has averaged returning echo strengths for the upper 22 cm of fine sand together with the next 18 cm of the lower compacted layer. Because of the way the sediment type database has been configured, the RASCL predicts that the 0 - 40 cm interval is composed of medium sand. However, the 30 kHz system which was operated such that it would predict sediment properties in 20 cm increments, defines two distinct layers in the first 40 cm (Table 1B). For the upper layer, RASCL predicts an impedance value of 2.72 which in the database corresponds to a fine sand. From 20 - 40 cm it gives an impedance value of 3.38 which is at the upper end of the medium sand range (nearly coarse sand). An average of the impedance values (2.72 and 3.38) for the first two layers is 3.05 which is close to that of 3.25 predicted by the 15 kHz system. Both frequencies would have predicted a medium sand as an average sediment type over the first 40 cm. It is interesting to note that the greater sensitivity of the 30 kHz system enabled it to predict exactly the sediment type for the upper fine sand layer. Because of the way the sediment type database is configured, RASCL had no choice but to predict a medium sand for the second interval with the 30 kHz and for the first 40 cm interval with the 15 kHz. No provision was made in the database for the hard compacted material below 22 cm.

TABLE 1

GULF SITE - SEDIMENT TYPE/STRUCTURE (CENTER)

A. 15 kHz

Ground Truth Core 18			RASCL Predicted		
Interval (cm)	Sediment Type	ϕ Mean	Interval (cm)	Sediment Type	Impedance
0 22	fine sand	2 4	0 - 40	medium sand	3 25

Structure Homogeneous

B. 30 kHz

Ground Truth Core 18			RASCL Predicted		
Interval (cm)	Sediment Type	ϕ Mean	Interval (cm)	Sediment Type	Impedance
0 - 22	fine sand	2 4	0 - 20	fine sand	2 72
			20 - 40	medium sand	3 38

Structure Several Homogeneous Layers

--- Layer (significant impedance change)

Table 2 gives the geotechnical and acoustic parameters measured on Core 18 and compares these values to those predicted by RASCL. It should be noted that it is nearly impossible to measure wet unit weight (density) and porosity accurately in sands in the laboratory using volumetric methods because of disturbance and a portion of the interstitial water between the sand grains migrates out of the sample before the analysis can be completed, i.e., complete saturation of the sample, at best, is difficult to maintain. Since the volumetric methods demand complete saturation of the sample to produce accurate results little faith can be put in values of density and porosity determined for sands by this method. The tendency is for the density to compute higher and the porosity to compute lower in laboratory analyzed sands that what the actual in situ conditions were for that sample. This appears to be true for the data collected from the Gulf site.

TABLE 2

GULF SITE (CENTER)
COMPARISON OF CORE DATA TO RASCL PREDICTED PROPERTIES

A. 15 kHz

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 - 40*	2.00*	1.89	11	40*	36	4	2.4*	1.5	9	1775*	1813	+38	3.25
Average Δ			11			-4			-9			+38	

* Core data 0 - 22 cm only

B. 30 kHz

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 - 20	2.00	1.67	33	40	46	+6	2.4	2.5	+.1	1775	1746	-29	2.72
20 - 40		1.93			34			1.1			1817		3.38
Average Δ			-33			+6			+.1			-29	

The comparison of the laboratory determined and 15 kHz RASCL-predicted properties is shown in Table 2A. The core data indicate a density of 2.00 g/cc while RASCL predicted 1.89 g/cc over the 0 - 40 cm interval for a difference of 0.11 g/cc. Similarly, the core data is higher than the RASCL data (40% to 36%) for values of porosity. In grain size the RASCL predicted a mean φ of 1.5 (medium sand) for the 0 - 40 cm interval while the core data gave a mean φ of 2.4 (fine sand) for an interval of 0 - 22 cm (total length of the core). These lower values are produced by averaging the fine sand layer with approximately 18 cm of the underlying compacted layer. Because of this, RASCL also predicted a higher sound velocity than was measured in the core.

In the comparison of the 30 kHz data with the core data the differences are more predictable because the 30 kHz system was set on a 20 cm increment. Here the core data indicate a bulk density of 2.00 g/cc for the fine sand layer while RASCL predicted a value of 1.67 g/cc for a difference of 0.33 g/cc (Table 2B). The RASCL predicted a porosity of 46% while the average porosity for the core was 40%. In light of the problems involved with accurately measuring density and porosity in the laboratory, it is likely that the RASCL-predicted values are more indicative of the in situ conditions at the Gulf Site than those measured on the core. The grain size data predicted by RASCL are essentially the same as measured on the core (2.5 to 2.4 φ) for the fine sand layer. The sound velocity data are similar also with a difference of only 29 m/sec. In the compacted layer RASCL estimated density at 1.93 g/cc, porosity at 34%, mean φ at 1.1, and sound velocity at 1877 m/sec.

Battleship Buoy

The sediments at the Battleship Buoy trackline midpoint (Core 4, Fig. 7) are composed of sandy clay in the upper 40 cm of the sediment column. From 40 cm to 120 cm they are clayey sand. Below this is a mixture of sand, silt and clay (Table 3). A total of nine RASCL tracklines were run across Battleship Buoy center. Two lines were run with the 15 kHz systems and were parallel to each other. The second line, Run 2, was offset to the north by about 10 m. Two 30 kHz lines (Run 1 and Run 2) traversed the same sea floor as the 15 kHz tracklines. Five 30 kHz lines (crossings) were run perpendicular to the previous tracklines over

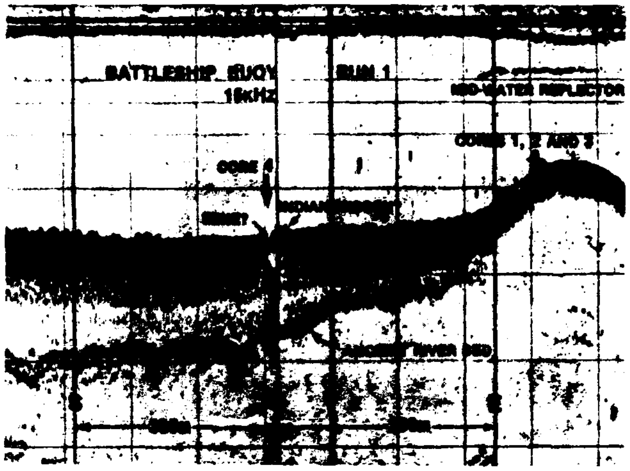

Figure 7. Battleship Buoy 15 kHz analog record.

Battleship Buoy center. Each crossing was shifted a few meters to the west of the previous crossing except the fifth which was run between Crossing 2 and Crossing 3. All nine of the RASCL tracklines predicted silty clay sediments for the first 40 cm of the sediment (Tables 3 and 4). Below 40 cm the four tracklines (Runs 1 and 2 for both the 15 and 30 kHz systems) showed the sediment to be composed of sandy clay instead of clayey sand. All of the crossings predicted silty clay for the upper 60 cm of sediment with sandy clay below (Table 4).

The 15 kHz system did an excellent job in predicting the sediment parameters in the upper 40 cm of the sea floor at this site (Table 5). Data from both runs is nearly identical with the first run calculating only slightly higher impedance values. As expected, the prediction accuracy of this system deteriorated somewhat with depth in the sediment. Between the two runs, the variation from the core data averaged 0.11 g/cc for density, 2% for porosity, 0.4 φ for grain size and 4 m/sec for sound velocity.

The 30 kHz system also performed well in predicting the sediment properties at this site. Overall, it was slightly more precise than the 15 kHz system in estimating density, porosity, and grain size with average variations of 0.03 g/cc, 2%, and 0.1 φ, respectively (Table 6). The prediction of sound velocity was a little less accurate with a difference of 9 m/sec.

The RASCL data from the first three crossings are equivalent to that of the two 30 kHz runs. Even though the crossing data showed the same sediment type to a depth of 60 cm instead of to just 40 cm as in the run data, the average difference from the ground truth data for density and porosity is identical. The agreement for grain size and sound velocity is slightly less due to the predicted extra 20 cm depth of the silty clay layer. Here the average variation increases to 0.7 φ for grain size and 17 m/sec for sound velocity.

Sediment Prediction Capability

A statistical analysis has been made of the core data versus RASCL-predicted values for density, porosity, grain size, and sound velocity. These data were statistically treated with a simple linear regression where a correlation coefficient was computed to indicate the sediment parameter prediction capabilities of the RASCL system in relation to the ground truth core measurements. Since, theoretically, the RASCL system should produce better prediction results for the initial sediment interval than with deeper intervals, a separate analysis was made for surface values only and another was made for all data available with depth in the sediment. An additional analysis was made comparing impedance calculated from the core data (density times sound velocity) to the impedance value computed by the RASCL system. Data from both frequencies (15 and 30 kHz) were combined in the comparisons since the available data for the 15 kHz system was somewhat limited, i.e., it was used on only four sites, two of which were sand environments with limited core data.

Both RASCL frequency configurations did extremely well overall in predicting the physical and acoustic properties of the surface sedi-

TABLE 3

BATTLESHIP BUOY - SEDIMENT TYPE/STRUCTURE (CENTER)

A. 15 kHz

Ground Truth			RASCL Predicted			
Core 16			Run # 1		Run #2	
Interval (cm)	Sediment Type	φ Mean	Sediment Type	Impedance	Sediment Type	Impedance
0 - 40	sandy clay	8 0	silty clay	1.74	silty clay	1 68
40 - 80	clayey sand	5 3	sandy clay	1 91	sandy clay	1 84
80 - 120	clayey sand	5 9	↓	↓	↓	↓
120 - 160	sand-silt-clay	5.5				

Structure: Layer Over Homogeneous

B. 30 kHz

Ground Truth			RASCL Predicted			
Core 16			Run # 1		Run #2	
Interval (cm)	Sediment Type	φ Mean	Sediment Type	Impedance	Sediment Type	Impedance
0 - 20	sandy clay	8 2	silty clay	1.64	silty clay	1 68
20 - 40	sandy clay	7 7	silty clay	1 65	silty clay	1.68
40 - 60	clayey sand	5 6	sandy clay	1 82	sandy clay	1 85
60 - 80	clayey sand	5 1	↓	↓	↓	↓
80 - 100	clay: / sand	5 8				
100 - 120	clayey sand	5 9				
120 - 140	sand-silt-clay	5 4				

Structure: Several Homogeneous Layers/Layer over Inhomogeneous — Structure: Layer over Inhomogeneous/Several Homogeneous Layers

.... Layer (significant impedance change)

TABLE 4

BATTLESHIP BUOY CROSSINGS SEDIMENT TYPE/STRUCTURE (CENTER)

30 kHz

Ground Truth			RASCL Predicted									
Core 4			Crossing #1		Crossing #2		Crossing #3		Crossing #4		Crossing #5	
Interval (cm)	Sediment Type	φ Mean	Sed. Type	Imp.	Sed. Type	Imp.	Sed. Type	Imp.	Sed. Type	Imp.	Sed. Type	Imp.
0 20	sandy clay	8 2	silty clay	1 68	silty clay	1 66	silty clay	1 67	silty clay	1 71	silty clay	1 66
20 40	sandy clay	7 7	silty clay	1 68	silty clay	1 66	silty clay	1 67	silty clay	1 71	silty clay	1.66
40 60	clayey sand	5 6	silty clay	1 68	silty clay	1 66	silty clay	1 67	silty clay	1 71	silty clay	1 66
60 80	clayey sand	5 1	sandy clay	1 82	sandy clay	1 82	sandy clay	1 84	sandy clay	1 87	sandy clay	1 82
80 100	clayey sand	5 8	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
100 120	clayey sand	5 9										
120 140	sand silt clay	5 4										
			Structure Several Homogeneous Layers		Structure Several Homogeneous Layers		Structure Several Homogeneous Layers		Structure Several Homogeneous Layers		Structure Several Homogeneous Layers	

··· Layer (significant impedance change)

TABLE 5

BATTLESHIP BUOY (CENTER)
COMPARISON OF CORE DATA TO RASCL PREDICTED PROPERTIES

A. 15 kHz - RUN # 1

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 40	1 24	1 24	0	84	85	+1	8 0	7 3	-7	1530	1527	-3	1 74
40 - 80	1 34	1 26	-18	78	78	0	5 3	5 9	+ 6	1545	1545	0	1 91
80 - 120	1 41	1 26	15	75	78	+3	5 9	5 9	0	1523	1545	+22	1 91
120 - 160	1 50	1 26	24	70	78	+8	5 5	5 9	+ 4	1530	1545	+5	1 91
Average Δ			-12			+3			+ 1			+6	

B. 15 kHz - RUN # 2

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 40	1 24	1 24	0	84	85	+1	8 0	7 9	-1	1530	1519	11	1 68
40 80	1 34	1 28	06	78	74	-4	[illegible]	6 5	+1 2	1545	1538	-7	1 84
80 120	1 41	1 28	-13	75	74	-1	5 9	6 5	+ 6	1523	1538	+15	1 84
120 - 160	1 50	1 28	-22	70	74	+4	5 5	6 5	+1 0	1530	1538	+8	1 84
Average Δ			[illegible]			0			+ 7			+1	
Two-Run Average Δ			-11			+2			+ 4			+4	

TABLE 6

BATTLESHIP BUOY (CENTER)
COMPARISON OF CORE DATA TO RASCL PREDICTED PROPERTIES

A. 30 kHz - RUN # 1

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 - 20	1 20	1 22	+ 02	87	89	+2	8 2	7 8	-4	528	1513	-15	1 64
20 - 40	1 29	1 22	-.07	81	89	+8	7 7	7 5	3	1532	1515	-17	1 65
40 60	1 29	1 25	-04	81	81	0	5 6	6 8	+1 2	1540	1536	-4	1 82
Average Δ			-03			+3			+ 2			12	

B. 30 kHz - RUN # 2

Interval (cm)	Wet Unit Weight (g/cc)			Porosity (%)			Grain Size (mean φ)			Sound Velocity (m/s)			Impedance
	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	Cores	RASCL	Δ	RASCL
0 - 20	1 20	1 23	+ 03	87	86	1	8 2	7 6	-6	1528	1519	[illegible]	1 68
20 - 40	1 29	1 23	-06	81	86	+5	7 7	7 6	-1	1532	1519	[illegible]	1 68
40 - 60	1 29	1 26	-03	81	77	-4	5 6	6 0	+ 4	1540	1539	-1	1 85
Average Δ			02			0			-1			-7	
Two-Run Average Δ			-03			+2			+1			-9	

ments (either the first 20 or 40 cm) with correlation coefficients for density, porosity, mean grain size, and sound velocity of 0.96, 0.95, 0.93, and 0.97, respectively. As expected, correlation was reduced when all depth intervals were considered and were 0.90, 0.81, 0.64, and 0.91 for these same properties, respectively. With the exception of the mean grain size (0.64), these correlations are considered excellent. Based on this result, the RASCL systems (either transducer) are capable of acceptable predictions of sediment properties in the sediment column within the limits of the acoustic signal penetration.

As a test of the algorithms used to compute sediment impedance in the RASCL software, the values of measured sound velocity and density from the core data were used to calculate a "measured" sediment impedance. These values were then compared to the corresponding RASCL-predicted impedance values for the same sediment depth intervals. The results of this comparison are shown in Fig. 8 which gives a correlation coefficient of 0.87. Thus, the RASCL system did extremely well overall predicting acoustic impedance indicating that the algorithms used are theoretically sound.

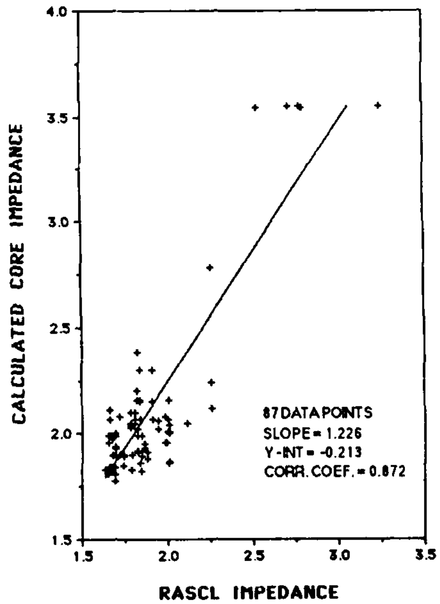

Figure 8. Correlation between calculated core impedance and RASCL computed impedance; includes both 15 kHz and 30 kHz data from all depth intervals.

CONCLUSIONS

Based on the foregoing discussion, several conclusions can be made of the RASCL seafloor classification system:

1) The RASCL system, consisting of the EMG2, LAZ 72, and either the 15 kHz or 30 kHz transducers, is a superb high resolution seismic profiling system in all sediment types tested.

2) The RASCL system is capable of the prediction of sediment type and several geotechnical properties within reasonable limits of precision while in a rapid survey mode. It estimates the properties of surficial sediments better than those deeper in the sediment column.

3) A strong correlation exists between RASCL-predicted impedance and impedance calculated from core data. This indicates that the algorithms used to estimate impedance at all sediment depths are reasonable.

4) Some knowledge of a particular environment is required before running a survey. The RASCL system will not completely eliminate sediment sampling as a few ground truth samples are required for calibration of the system.

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